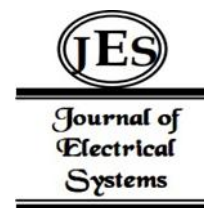


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Comprehensive Review on Intelligent controller for Permanent Magnet Synchronous motor



Abstract: - The energy-saving permanent magnet synchronous motor (PMSM) is a very effective device. In many industrial applications, PMSMs are progressively taking the place of AC induction motors due to their high efficiency, strong heat radiation capabilities, and simple structural features. A PMSM basically needs a intelligent controller to provide precise speed monitoring, little overshoot, and strong disturbance repulsion in order to operate at an excessive level. This paper presents a comprehensive review of control strategies for PMSMs, focusing on both traditional and intelligent control methods. Traditional control techniques such as Proportional-Integral-Derivative (PID), Direct Torque Control (DTC), and Field-Oriented Control (FOC) are examined for their efficacy and applications in PMSM systems. Additionally, the paper explores advanced intelligent control methodologies including Artificial Neural Networks (ANN), Fuzzy Logic Control, Adaptive Neuro-Fuzzy Inference System (ANFIS), Model Predictive Control (MPC), and Sliding Mode Control (SMC). The review also highlights the tuning of PI controllers using various optimization procedures, providing a detailed comparison of these methods in terms of performance, robustness, and implementation complexity. Through this analysis, the paper aims to offer valuable insights into the advancements in control strategies for PMSMs, guiding future research and development in this field.

Keywords: Permanent Magnet Synchronous Motors, Intelligent Control Strategies, Artificial Neural Networks (ANN), Fuzzy Logic Control, Adaptive Neuro-Fuzzy Inference System (ANFIS).

I. INTRODUCTION

PMSM are increasingly popular in various industrial applications because of their good efficacy, best size, and superior performance characteristics. The precise control of PMSMs is crucial to fully exploit these benefits, leading to the development of intelligent controllers that enhance the motor's performance, reliability, and efficiency. This review explores the various intelligent control techniques employed for PMSM control, highlighting their advantages and limitations

A hybrid intelligent control for interior PMSM drives was implemented in [1]. The key result of this analysis was the successful application of the hybrid intelligent controller in improving the running of the motor drive system. The limitation of this study could be the lack of real-time implementation and testing of the controller in a practical industrial setting, which may affect the generalizability of the results.[2] discussed on control of PMSM drive systems using various controllers. The study compared the functioning of PI, PID, SMC, and SMC plus PID controllers in controlling the speed of the motor drive system. One limitation of this study could be the limited scope of comparison between the controllers, as other advanced control strategies could also be considered for a more comprehensive analysis.[3] investigated the field-oriented control of PMSM using a PID controller. The study aimed to optimize the motor's performance by implementing the PID controller in the control system. A limitation of this study may be the assumption of ideal conditions in the simulation models.[4] proposed a direct torque controller for PMSM. The study focused on improving the torque control of the motor drive system through the implementation of the direct torque controller. One limitation of this study could be the lack of comparison with other torque control strategies, which could provide a more comprehensive evaluation of the proposed controller.[5] presented a robust speed-controlled permanent magnet synchronous motor drive using a FLC. The study aimed to improve the control working of the motor drive system by incorporating fuzzy logic control. A limitation of this study may be the complexity of tuning the fuzzy logic controller parameters, which could affect the control strategy's ease of implementation and practicality.

The study by [6] proposed an artificial neural network-based SPWM technique for speed control of PMSM. The limitation of this study could be the lack of real-time implementation of the proposed technique, which may affect its practical applicability.[7] focused on the design and performance analysis of an ANFIS for speed control of PMSM drives. One limitation of this study could be the complexity and computational overhead associated with implementing an ANFIS controller in real-time applications.[8] presented a fuzzy scheme relied on GA to control PMSM. A limitation of this study could be the potential challenges in tuning the fuzzy controller parameters using genetic algorithms, which may require extensive computational resources.[9] focused on enhancing the performance of MPC for permanent magnet synchronous motor drives. One limitation of this research could be the complexity and computational burden associated with implementing model-predictive control procedures in different applications.[10] discussed the optimization of an flux-weakening approach for PMSM using a PSO procedure. A limitation of this study could be the potential challenges in achieving convergence and optimal solutions when using PSO for parameter optimization in complex motor control systems.

A global optimization procedure for developing and manipulating PMSM drives was proposed by [11]. The key result of the work was the development of an efficient optimization method for enhancing the performance of these motor drives. The study focused on a specific optimization technique and did not compare it with other existing methods, potentially limiting the generalizability of the results.[12] presented a revised design of a PID regulator for PMSM drives using PSO. The key finding was the improved performance of the motor drive scheme through the optimized PID control design. The study did not explore the

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robustness of the proposed controller design under varying operating conditions, which could affect its practical applicability.[13] introduced a GWO procedure relied state response control for a bearing less PMSM. The study displayed the efficacy of this control approach in enhancing the operational efficiency of the machine. The research did not investigate the real-time implementation challenges or computational complexity associated with the proposed control algorithm, which could impact its feasibility in practical applications.[14] conducted a comparative assessment of control procedures for performing internal PMSM drive systems. The study aimed to estimate the working of numerous intelligent control approaches in enhancing the motor drive system's efficiency. The study's scope was limited to internal PMSM drives, potentially overlooking the applicability of the findings to another kinds of motor schemes.[15] proposed a hybrid control strategy for PMSM-relied standalone wind with battery energy storage systems. The study highlighted the benefits of integrating multiple control techniques to optimize the performance of wind turbine systems. The research did not address the potential challenges associated with the integration of different control strategies, such as coordination issues or increased complexity, which could affect the overall system reliability.

II. OPERATION & CONTROL LOGIC OF PMSM

A PMSM operates by combining the RMF generated by the stator windings with the magnetic field generated by the rotor's permanent magnets. AC currents are sent into the stator, which is usually made up of three-phase windings and produces a revolving magnetic field. The rotor turns synchronously with the revolving magnetic field when this field interrelates with the permanent magnets in the rotor, producing torque. Compared to other motor types, the use of permanent magnets eliminates the requirement for brushes and commutators, ensuing in increased efficiency, lower protection, and quieter operation. Because of its synchronous operation, which guarantees accurate speed control when the rotation rate of the rotor equals the frequency of the AC supply, PMSMs are perfect for high-performance and reliable applications including robotics, industrial automation, and electric cars. Advanced approaches like FOC or DTC are commonly used to operate PMSMs. These techniques optimize performance and efficiency by managing the stator currents in a way that sets the motor's speed and torque. The following formulas explain the mathematical model of a PMSM drive.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R + PL_d & -P\omega_r L_q \\ P\omega_r L_d & R + PL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ P\omega_r \psi_f \end{bmatrix} \quad (1)$$

$$T_e = T_L + J_m p \omega_r \quad (2)$$

$$T_e = \frac{3P}{2} (\psi_f i_q + (L_d - L_q) i_d i_q) \quad (3)$$

If the stator currents are $i_d, i_q = d$ and q -axis and the stator potentials, $L_d, L_q = d, q$ axis stator inductances; R = stator per phase resistance electromagnetic and load torques, T_e, T_L, J is the motor's and the load's moment of inertia.

Control Logic

To accomplish high-performance speed tracking, the aim of this study is to get the PWM voltages for the PMSM drive. In as much as the $-d$ -axis current is kept at zero, it is possible to regulate the speed throughout the standard mode of control for the purpose of evaluating the novel approach that has been suggested.

$$P i_q = \frac{1}{L_q} (v_q - R i_q - P \omega_r \psi_f) \quad (4)$$

$$v_d = -P \omega_r L_q i_q \quad (5)$$

$$T_e = T_L + J_m P \omega_r + B_m \omega_r \quad (6)$$

$$T_e = \frac{3P}{2} (\psi_f i_q) \quad (7)$$

Need for controller in PMSM

Controllers for PMSM are essential for ensuring precise operational control in various applications. They enable precise regulation of speed and torque, critical for applications requiring accurate motor performance. By optimizing the stator currents based on load conditions, controllers enhance motor efficiency, reducing energy consumption and operating costs. They also improve the motor's dynamic response, swiftly adapting to changes in load or speed to maintain stability and responsiveness. Moreover, controllers handle inherent non-linearities in motor behavior, ensuring smooth operation and reducing performance fluctuations. They contribute to quieter motor operation by minimizing torque ripple and mechanical vibrations, enhancing comfort and usability across different environments.

Controllers significantly enhance the reliability and longevity of PMSMs by integrating fault detection and correction mechanisms, ensuring consistent operation and reducing downtime and maintenance costs. Their adaptability to varying conditions makes them suitable for diverse applications, including electric vehicles and industrial automation. By extending maintenance intervals and minimizing component wear, controllers contribute to cost savings and operational efficiency. In summary, controllers

are crucial for maximizing the performance, efficiency, and reliability of PMSMs, meeting the stringent demands of modern industrial and automotive sectors.

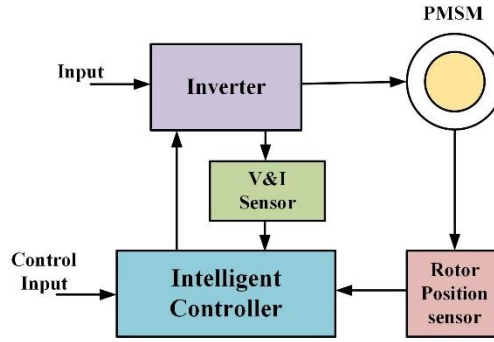


Fig.1 Representation of PMSM Control

III. TRADITIONAL CONTROLLER

Traditional control methods for PMSMs include Proportional-Integral-Derivative (PID) control, FOC, and DTC.

PID Control

PID control is popular in industrial applications due to its simplicity and effectiveness. It adjusts the control input based on three terms. The proportional term reduces rise time and eliminates most of the steady-state error, the integral term aims to eliminate the error by integrating the error over time, and the derivative term reflects the rate of variation of the error, improving system stability and transient response. However, PID controllers have limitations, including sensitivity to parameter variations, limited robustness, and difficulty in handling non-linearities.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (8)$$

Field-Oriented Control

FOC, also known as vector control, is a more sophisticated method that decouples the motor's torque and flux, permitting standalone control of these components. FOC uses mathematical transformations to separate the torque-producing and flux-producing currents, employing two separate control loops and transforming the control signals back into 3-phase signals via a PWM inverter. FOC provides high performance with improved efficiency, precise torque control, and better dynamic response but requires complex mathematical transformations and accurate motor parameters, making it sensitive to parameter variations.

$$V_d = R_s I_d + L_d \frac{di_d}{dt} - \omega L_q I_q \quad (9)$$

$$V_q = R_s I_q + L_q \frac{di_q}{dt} - \omega L_d I_d + \omega \lambda_m \quad (10)$$

Direct Torque Control

DTC focuses completely on controlling the motor's torque and flux without the decoupling process used in FOC. DTC estimates the motor's torque and flux from stator voltages and currents, selecting appropriate inverter switching states from a predefined switching table. This results in a fast torque response and high dynamic performance. However, DTC can produce high torque and flux ripples, leading to increased acoustic noise and vibration, and it also relies on accurate motor parameter estimation.

Stator flux linkage estimation

$$\lambda_s = \int (V_s - R_s I_s) dt \quad (11)$$

Electromagnetic Torque estimation

$$T_e = \frac{3}{2} P (\lambda_s \times I_s) \quad (12)$$

While traditional methods like PID, FOC, and DTC are effective, they each have limitations. PID control, though simple, is less robust and struggles with non-linearities. FOC provides precise control and efficiency but is complex and parameter sensitive. DTC offers a fast dynamic response but suffers from torque ripple and parameter sensitivity. These limitations have led to the development of intelligent control methods aimed at overcoming these challenges and enhancing PMSM performance.

IV. INTELLIGENT CONTROLLERS

Fuzzy Logic Control (FLC)

Fuzzy Logic is one of the earliest intelligent control methods applied to PMSMs. FLC mimics human decision-making and is effective in handling non-linearities and uncertainties. It does not require a precise mathematical model of the motor, making it robust against parameter variations. However, designing an effective fuzzy inference system can be complex and requires expert knowledge. FLC uses fuzzy logic to map inputs (error and change in error) to an output control action based on a set of linguistic rules.

Fuzzification:

If $e(t)$ is A_i and $\Delta e(t)$ is B_j , then $u(t)$ is C_{ij}

A_i, B_j are fuzzy sets for error and change in error. C_{ij} is the control action.

Defuzzification (Centroid method)

$$u(t) = \frac{\sum_{i=1}^n \sum_{j=1}^m \mu_{A_i}(e) \mu_{B_j}(\Delta e) C_{ij}}{\sum_{i=1}^n \sum_{j=1}^m \mu_{A_i}(e) \mu_{B_j}(\Delta e)} \quad (13)$$

Where, μ_{A_i}, μ_{B_j} are the membership functions.

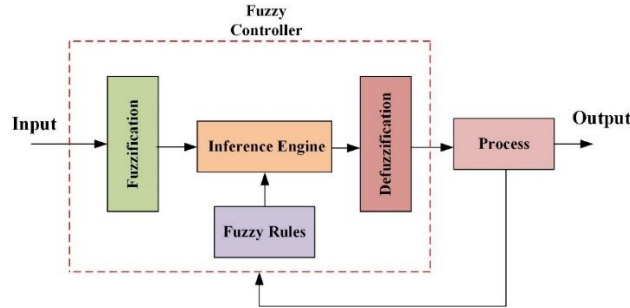


Fig.2 Concept of Fuzzy control

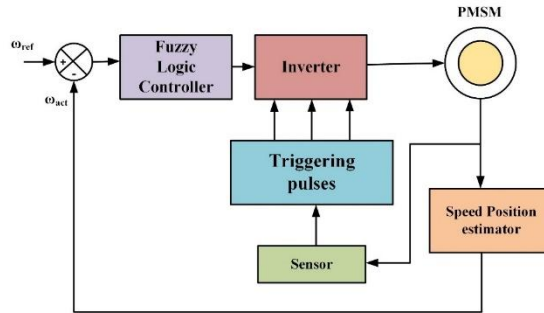


Fig.3 PMSM using Fuzzy control

Artificial Neural Network (ANN)

ANN is employed networks to learn and adapt to the control of PMSMs. These networks can approximate non-linear functions and adapt to changing conditions, providing high performance in dynamic environments. The primary challenges with NNC include the need for extensive training data and computational resources, and the potential for overfitting. ANN control employs a neural network to approximate the control function.

$$y_i = f(\sum_{j=1}^n \omega_{ij} x_j + b_i) \quad (14)$$

where:

y_i is the output of the i-th neuron.

ω_{ij} is the weight from neuron j to neuron i.

x_j is the input.

b_i is the bias.

f is the activation function, commonly sigmoid or ReLU

Training & Back propagation

$$\Delta \omega_{ij} = -\eta \frac{\partial E}{\partial \omega_{ij}} \quad (15)$$

where:

$\Delta \omega_{ij}$ is the weight update.

η is the learning rate.

E is the error function.

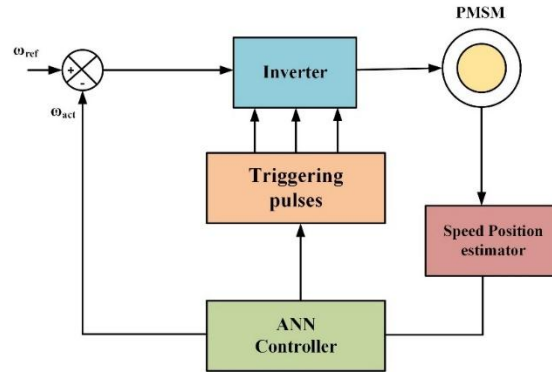


Fig.4 PMSM using ANN control

Adaptive Neuro-Fuzzy Inference System (ANFIS)

ANFIS relates the learning potentials of neural networks with the fuzzy logic approach to create a hybrid intelligent controller. It offers the robustness of FLC and the adaptability of NNC, making it suitable for complex and non-linear systems like PMSMs. ANFIS controllers can self-tune to optimize performance, but their design and implementation can be intricate and computationally intensive. ANFIS combines neural networks and fuzzy logic principles to model non-linear functions.

Fuzzy inference

$$f(x) = \sum_{i=1}^N \omega_i \cdot f_i(x) \quad (16)$$

Learning (Hybrid Algorithm combining gradient)

$$\Delta\theta = -\eta \frac{\partial E}{\partial \theta} \quad (17)$$

where:

- ω_i are the firing strengths of the fuzzy rules.
- $f_i(x)$ are the consequent functions.
- θ are the parameters to be optimised.

Sliding Mode Control (SMC)

SMC is a dynamic control technique that is unaffected by variations in loads and motor characteristics. A switching method is employed in SMC to allow the system to trace a specified route (sliding surface) on the phase line. It can be regulated, in theory, by modifying the closed loop's dynamic behavior to conform to the sliding surface. The PMSM model's torque equation is provided as

$$\omega_r(t) = \frac{1.5 \times P \times \lambda \times i_q - B \times \omega - T_L}{J} \quad (18)$$

the surface is given by

$$S = e(t) + \frac{3 \times P \times \lambda}{2 \times J} \int e(t) dt \quad (19)$$

and the output can be explained as:

$$i \times q = qe + f \times \text{sgn}(S) + \frac{2 \times J}{3 \times P \times \lambda} \omega \quad (20)$$

where TL stands for load torque, J for moment of inertia variation, and q and f for gains. A sign function is function $\text{sgn}(S)$, which is defined as

$$\text{sgn}(S) = \begin{cases} +1 & \text{if } s > 0 \\ -1 & \text{if } s < 0 \end{cases} \quad (21)$$

The one component of SMC that must be avoided in specific applications, such as industrial automatons and machine tools, is the chatter that is impacted by the switching function after it doubles the sliding mode. This is SMC's weakest point.

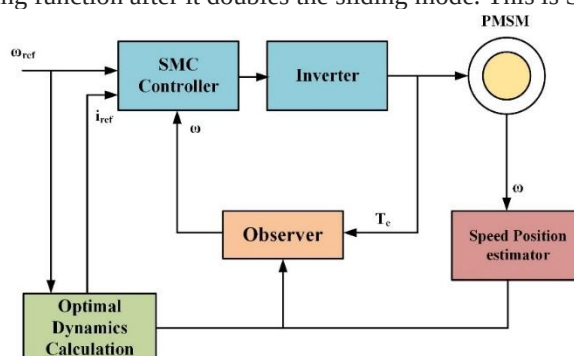


Fig.5 PMSM using SMC control

Model Predictive Control (MPC)

MPC is a sophisticated control procedure that predicts future states of the approach via a model and optimizes control actions in response. Because MPC can manage restrictions and multi-variable systems, it is quite effective for PMSMs. Using a discrete-time state-space model, MPC for a PMSM entails optimizing control inputs according to a cost function and forecasting future states. The MPC optimization problem is formulated using the state-space model, cost function, and constraints equations. It is solved repeatedly to guarantee the PMSG's optimal performance and stability. By maximizing a computed cost function, the MPC control strategy employs these data to determine the mechanism sequence for the schemes control. It is important to state that the algorithm runs for each sample period, and at moment k , the system may only use the first optimized result. Although the cost function can take on any shape, it is often described as

$$g = \sum_{i=1}^n \lambda_i (x_i^* - x_i^p)^2 \quad (22)$$

When λ_i is a weighting factor, index i indicates the controlled variables, and x_i^* is the reference instruction and anticipated value for variable x_i . It may be used to suggest variable control objectives, including constraints and non-linearities (in the case of several variables) in a simple manner.

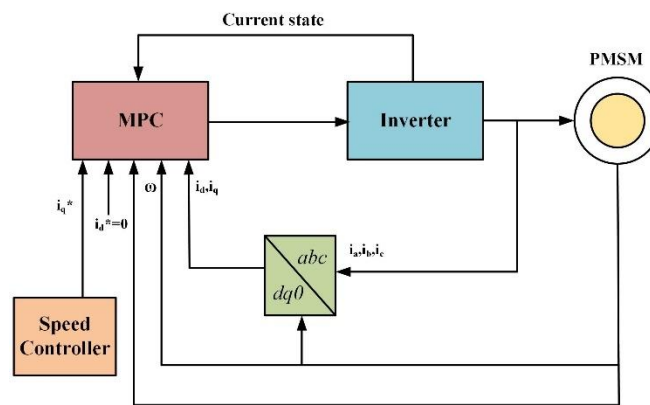


Fig.6 PMSM using MPC control

Optimization Algorithms for Controller Tuning

Another control method is to use new optimization algorithms to tune PI Controller parameters in order to obtain the desired value.

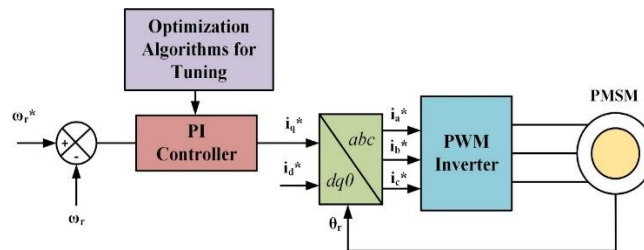


Fig.7 PMSM control using Optimization Algorithms

Genetic and Particle Swarm Optimization (PSO)

PMSM control parameters are optimized by use of algorithms such as PSO and GA. These algorithms improve the performance of controllers like PID, FLC, and MPC by locating optimum solutions in intricate, multi-dimensional domains. However, because they demand a lot of work and are not appropriate for real-time control, they are usually utilized offline. Based on the ideas of population genetics and natural evolution, these are exploratory search and optimization techniques. In contrast to conventional optimization methods, genetic algorithms (GAs) use random search and competition to change a population of people denoted by bit strings. The benefits that the GA offers over other conventional optimization methods may be summed up as follows.

1. GAs explore the issue space via a population of trials that represent potential solutions. The GA will be less likely to become stranded on local minima because of this characteristic.
- 2) GAs direct their search inside the issue space using an evaluation of the performance index.
- 3) GAs base their choices on probabilistic rules.

The process of reproduction creates a new generation of people by choosing the healthiest members of the existing population. In a GA, crossover is the most powerful operator. It is in charge of creating new offspring by choosing two strings and switching around some of their structural components. The weaker members of the population may be replaced by the new progeny. The application of mutation, a local operator, is quite rare. Its purpose is to change a string's random position's value.

PSO

In the context of PMSMs, PSO can be applied to tune the parameters of controllers such as PI controllers, which are critical for ensuring precise speed and torque control. The process involves the following steps:

Initialize the Particle Swarm:

- A set of particles (candidate solutions) is initialized with random values for the PI parameters (proportional gain (K_p), integral gain (K_i)).

Evaluate Fitness:

Each particle's fitness is evaluated by simulating the PMSM system with the corresponding PID parameters and calculating the objective function.

Update Velocities and Positions:

Particles adjust their locations and velocities according to the swarm's determination of the global optimal position as well as their individual best-known positions.

Iterate:

Until convergence requirements, like a maximum iterations or a tolerable error threshold, are satisfied, the process iterates.

Advantages of Using PSO for PMSM Control.

- The algorithm is easy to implement and requires few parameters to adjust, making it suitable for real-time applications.
- PSO can be adapted to tune various types of controllers and can handle different performance criteria and constraints.
- The algorithm is robust against changes in system dynamics and external disturbances, ensuring stable and reliable motor control.

The summary of the review of Controllers of the PMSM is presented in Table.1

Table.1 Comparison of Controllers of PMSM

Controller Type	Description	Advantages	Disadvantages
PID Control [2]	Adjusts control input based on proportional, integral, and derivative terms.	Simple, effective, widely used in industrial applications.	Sensitive to parameter variations, limited robustness.
FOC [3]	Decouples motor's torque and flux, allowing for independent control using mathematical transformations.	High performance, improved efficiency, precise torque control.	Complex mathematical transformations, sensitive to parameter variations.
DTC [4]	Directly controls motor's torque and flux without decoupling, using stator voltages and currents.	Fast torque response, high dynamic performance.	Produces high torque and flux ripples, relies on accurate motor parameters.
FLC [5]	Mimics human decision-making, handling non-linearities and uncertainties using fuzzy logic.	Robust against parameter variations, handles non-linearities.	Designing effective fuzzy inference system requires expert knowledge.
ANN [6]	Utilises artificial neural networks to learn and adapt control of PMSMs.	High performance in dynamic environments, adapts to changes.	Requires extensive training data and computational resources.
ANFIS [7]	Combines fuzzy logic with neural networks for a hybrid intelligent controller.	Robust and adaptive, suitable for complex, non-linear systems.	Design and implementation are intricate and computationally intensive.
SMC [2]	Nonlinear control method that is insensitive to changes in motor parameters and loads.	Insensitive to parameter changes, effective for non-linear systems.	Can produce chattering, affecting performance in some applications.
MPC [9]	Uses system model to predict future states and optimize control actions based on a cost function.	Handles multi-variable systems and constraints effectively.	High computational requirements, complex implementation.
GA [8]	Evolutionary algorithm inspired by natural selection for optimizing control parameters.	Less susceptible to local minima, searches problem space broadly.	High computational requirements, not suitable for real-time control.
PSO [10],[11]	Swarm intelligence algorithm inspired by social behavior of birds/fish for optimizing control parameters.	Fast convergence, easy to implement.	Can get trapped in local minima, requires fine-tuning of parameters.

V. CONCLUSION

This comprehensive review underscores the critical importance of advanced control strategies for the optimal performance of PMSM. Traditional control methods such as PID, DTC, and FOC have been foundational in PMSM applications, offering simplicity and reliability. However, their limitations in handling non-linearities and parameter variations necessitate the adoption of more sophisticated approaches. Intelligent control methodologies, including ANN, FLC, ANFIS, MPC, and SMC demonstrate significant improvements in precision, robustness, and adaptability. These methods address the complexities inherent in PMSMs, such as high-order dynamics and non-linear behaviors, providing enhanced speed regulation, reduced overshoot, and robust disturbance rejection. Furthermore, the integration of optimization algorithms like GA and PSO for tuning PI controllers is highlighted as a crucial advancement, facilitating the fine-tuning of control parameters to achieve optimal performance. In conclusion, while traditional control methods remain relevant, the evolution towards intelligent control strategies marks a significant leap in enhancing the efficiency and reliability of PMSMs. This review provides a foundational understanding and paves the way

for future research, encouraging the continued exploration and development of intelligent control systems in industrial applications. Overall, the choice of controller depends on the specific application requirements, balancing performance, complexity, and robustness.

REFERENCES

- [1] Uddin, M. N., Abido, M. A., & Rahman, M. A. (2004). Development and implementation of a hybrid intelligent controller for interior permanent-magnet synchronous motor drives. *IEEE Transactions on Industry Applications*, 40(1), 68-76.
- [2] Suman, K., & Mathew, A. T. (2018, September). Speed control of permanent magnet synchronous motor drive system using PI, PID, SMC and SMC plus PID controller. In *2018 international conference on advances in computing, communications and informatics (ICACCI)* (pp. 543-549). IEEE.
- [3] Maji, P., Panda, G. K., & Saha, P. K. (2015). Field oriented control of permanent magnet synchronous motor using PID controller. *Advanced Research in Electrical, Electronics and Instrumentation Engineering*, 4(2), 632-639.
- [4] Zhong, L., Rahman, M. F., Hu, W. Y., Lim, K. W., & Rahman, M. A. (1999). A direct torque controller for permanent magnet synchronous motor drives. *IEEE transactions on Energy Conversion*, 14(3), 637-642.
- [5] Dewantoro, G., & Kuo, Y. L. (2011, June). Robust speed-controlled permanent magnet synchronous motor drive using fuzzy logic controller. In *2011 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE 2011)* (pp. 884-888). IEEE.
- [6] Tummala, S. K., & Dhasharatha, G. (2019). Artificial neural networks based SPWM technique for speed control of permanent magnet synchronous motor. In *E3S web of conferences* (Vol. 87, p. 01030). EDP Sciences.
- [7] Shanthi, R., Kalyani, S., & Devie, P. M. (2021). Design and performance analysis of adaptive neuro-fuzzy controller for speed control of permanent magnet synchronous motor drive. *Soft Computing*, 25(2), 1519-1533.
- [8] Öztürk, N., & Çelik, E. (2012). Speed control of permanent magnet synchronous motors using fuzzy controller based on genetic algorithms. *International Journal of Electrical Power & Energy Systems*, 43(1), 889-898.
- [9] Zhang, Y., Xu, D., Liu, J., Gao, S., & Xu, W. (2017). Performance improvement of model-predictive current control of permanent magnet synchronous motor drives. *IEEE Transactions on Industry Applications*, 53(4), 3683-3695.
- [10] Xu, W., Ismail, M. M., Liu, Y., & Islam, M. R. (2019). Parameter optimization of adaptive flux-weakening strategy for permanent-magnet synchronous motor drives based on particle swarm algorithm. *IEEE Transactions on Power Electronics*, 34(12), 12128-12140.
- [11] Ganguli, S., Kumar, A., Kaur, G., Sarkar, P., & Rajest, S. S. (2021). A global optimization technique for modeling and control of permanent magnet synchronous motor drive. *Innovations in Information and Communication Technology Series*, 074-081.
- [12] Baskin, M., & Caglar, B. (2014, September). A modified design of PID controller for permanent magnet synchronous motor drives using particle swarm optimization. In *2014 16th International Power Electronics and Motion Control Conference and Exposition* (pp. 388-393). IEEE.
- [13] Sun, X., Jin, Z., Cai, Y., Yang, Z., & Chen, L. (2020). Grey wolf optimization algorithm based state feedback control for a bearingless permanent magnet synchronous machine. *IEEE Transactions on Power Electronics*, 35(12), 13631-13640.
- [14] Uddin, M. N. (2003, May). Comparative analysis of intelligent controllers for high performance interior permanent magnet synchronous motor drive systems. In *Large Engineering Systems Conference on Power Engineering*, 2003 (pp. 50-54). IEEE.
- [15] Khazaal, H. F., Hburi, I. S., Farhan, M. S., & Dininawi, M. (2020, March). A hybrid control strategy for PMSG-based standalone wind turbines with BESS. In *IOP Conference Series: Materials Science and Engineering* (Vol. 745, No. 1, p. 012012). IOP Publishing